Field error correction and warm measurements in HQ

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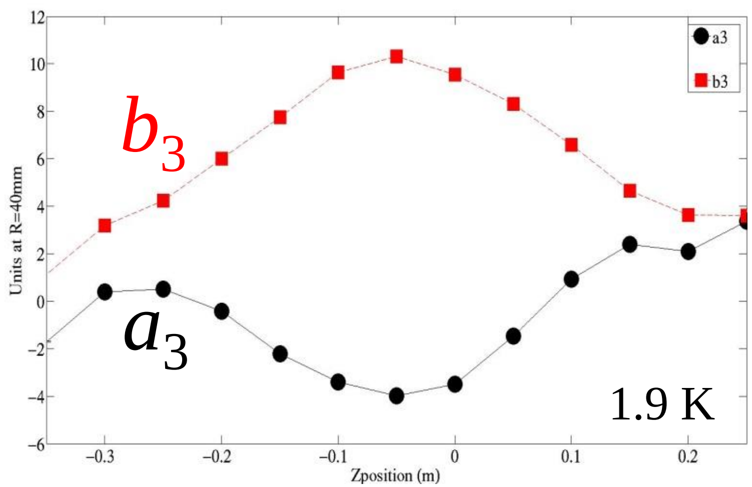
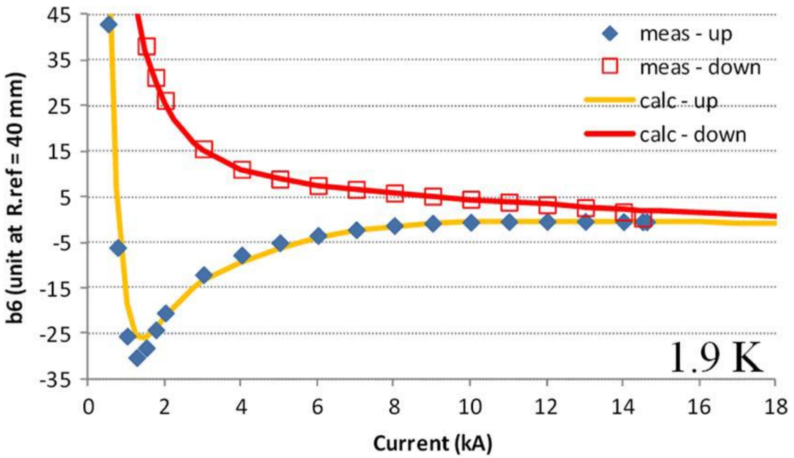
HQ as a test bed for field error correction

- HQ02 is the latest data point to project QXF performance
- Good field quality observed in HQ02 but a few open issues are also identified
  - Geometric errors along the straight section with a systematic variation
  - Large persistent-current effect around injection level (108/127 conductor)



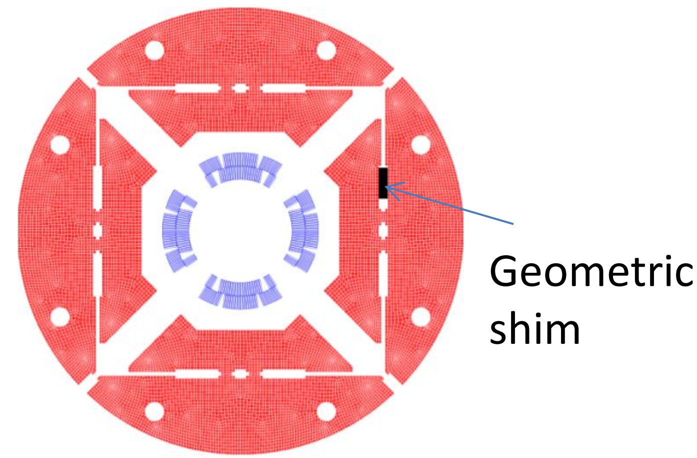


DiMarco *et al.*, IEEE TASC, 4003905, 2014

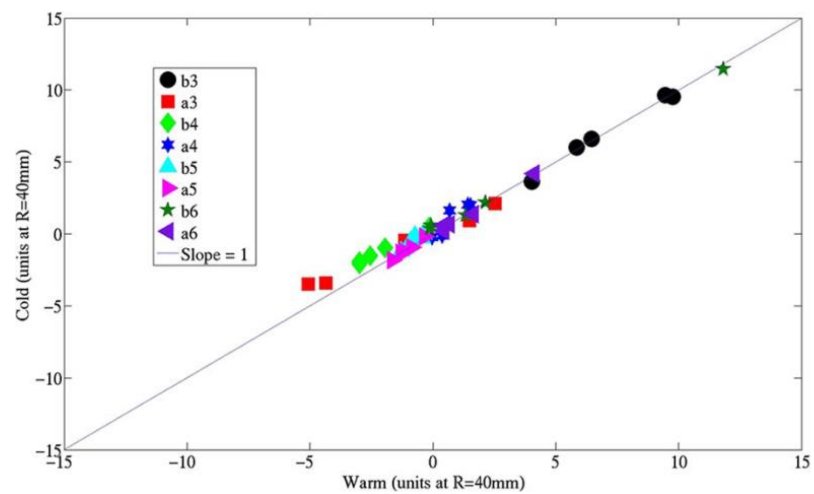
- Techniques are available to correct these effects
- Use HQ02/3 to verify correction scheme performance for implementation in QXF
- Shim implementation and warm (room temperature) measurements in HQ02b

Geometric errors and correction

- Magnetic shims away from the aperture to compensate field errors at nominal level
  - Tunable permeability to compensate low-order errors
- Successful cases for RHIC [Gupta et al., IEEE MAG, 1996, p. 2069] and HGQ (MQXB model) [Sabbi et al., IEEE TASC, 2000, p. 123] and plans for QXF [Hagen, WP3 report MS36]

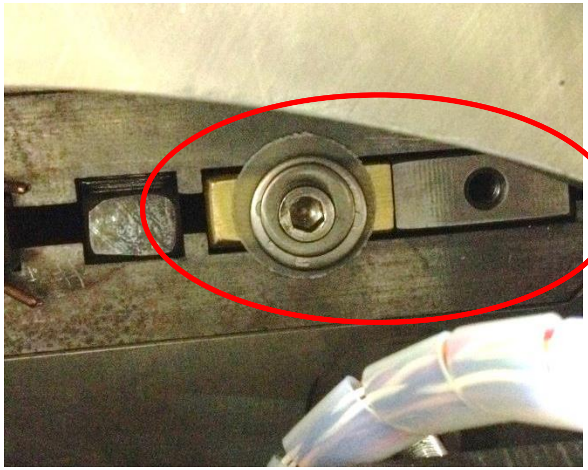


- Good warm-cold correlation a necessary condition for warm installation
  - True for HQ02a (and same expected for HQ03)
- Use warm measurements to determine the required shimming implementation

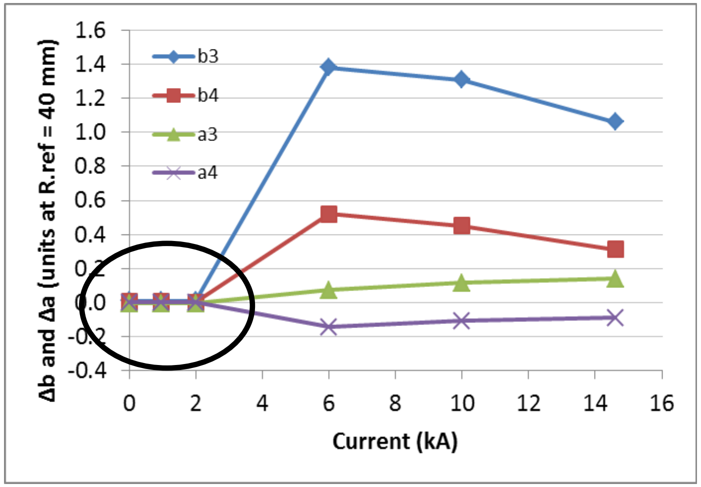


DiMarco *et al.*, IEEE TASC, 4003905, 2014

Test implementation in HQ02b



- Verify the mechanical compatibility with magnet (easy installation, well constrained during operation)
- One shim was fabricated (brass + low-carbon steel)
- Inserted in the bladder slot covering the entire magnet length
- *No negative impact* on magnet performance during the cold test



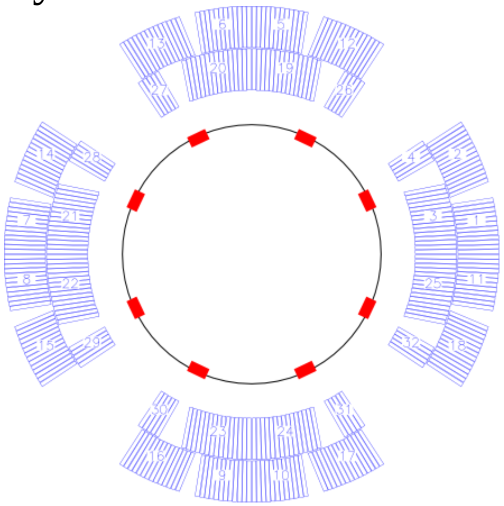
- Calculation shows negligible effect below 2kA
- High-accuracy measurements and computation are critical to guide implementation
- Correction capability of a few units (b3/a3, b4/a4)
- Full shims are planned to be implemented in HQ03 as a first test

Persistent-current effect correction

- Magnetic shims inside the aperture to
  - Compensate the persistent-current effect at low field
  - Saturate and become transparent at nominal level
  - Proposed and successfully tested in FNAL Nb_3Sn dipole HFDA02
    [Kashikhin *et al.*, IEEE TASC, 2003, p. 1270]

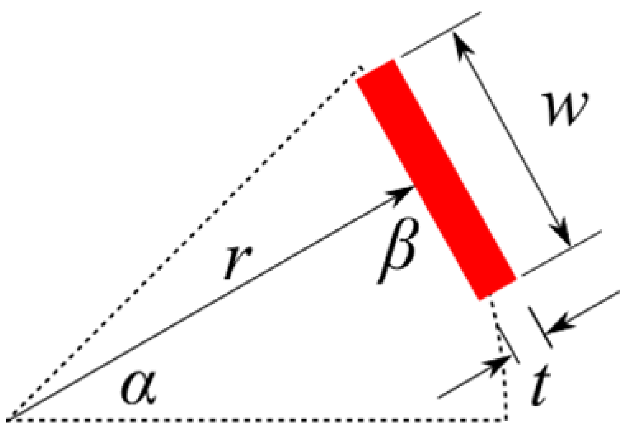
- With uniform conductor property, persistent currents affect allowed harmonics due to the symmetry
  - Shim properties must satisfy the same symmetry

- Implementation in HQ02b to study the shim fabrication and installation
  - 8 shims mounted on a tube fixed inside the magnet aperture
  - Shim parameters designed to reduce the peak b_6 at 1250 A as observed in HQ02a



Main parameters

- Magnetic property: permeability (low-carbon steel 1010)
- Geometric properties: radius (tube/beam pipe OD), angular position, width, thickness

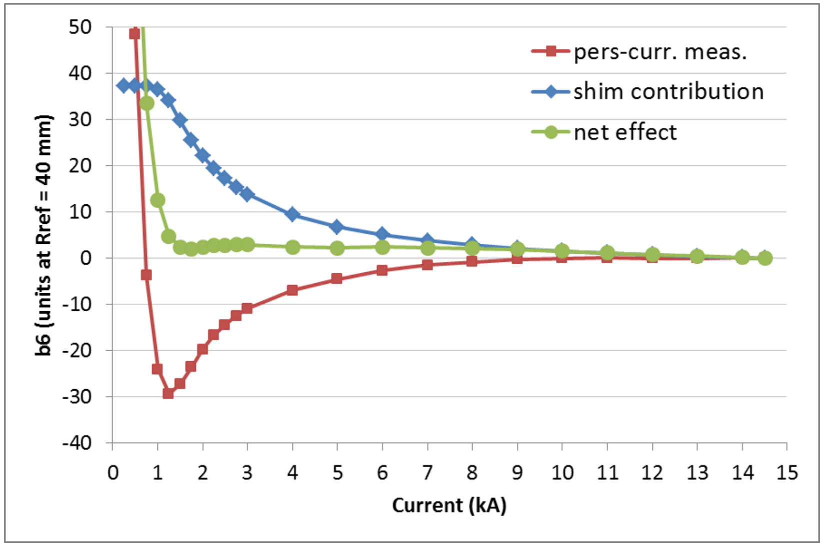


Item	Nominal	Tolerance
Radius (r)	46.36 mm	± 0.1 mm
Angle (α)	25.3 deg	± 0.1 deg (± 80 μm)
Width (w)	1.59 mm	± 0.1 mm
Thickness (t)	0.46 mm	± 0.02 mm
Tilt (β)	90.0 deg	± 0.5 deg (± 10 μm)

- Tolerance levels were estimated for the first HQ02b implementation and can be improved further for next round of implementations
- The impact of shim geometric tolerances on field quality was evaluated

Example expected shim effects for HQ

- Significant reduction of b_6 variation around injection level. Peak value reduces from -30 units to 5 units



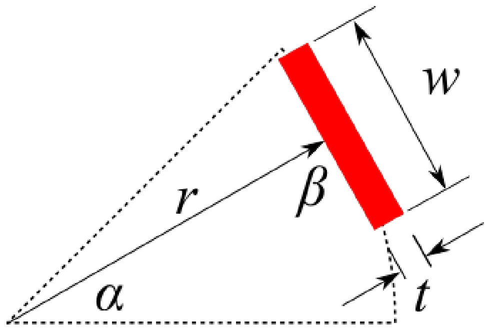
1250 A	Before correction	After correction
b_6	-32	5.8
b_{10}	1.4	-1.8
b_{14}	0	-21.9
b_{18}	0	9.3
b_{22}	0	6.9
b_{26}	0	-5.1
b_{30}	0	-1.6

R_{ref} = 40 mm

- Higher-order terms appear at low field but negligible at nominal level
- Based on initial AP feedback, final scheme may require additional shims to avoid higher-order effects

Impact of shim geometric tolerances

- Consider the same variation for all shims, only allowed terms are affected
- R_{ref} = 40 mm (1/3 magnet aperture)



- The actual shim is 0.8 mm wider than the design value due to the tooling issue
- Still useful for warm measurements

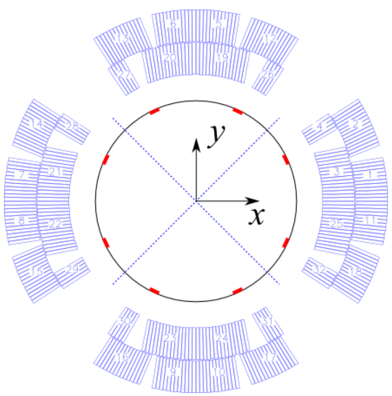
Δb_n given here are for positive variation

Parameter	Nominal	Variation range	Δb_6	Δb_{10}	Δb_{14}	Δb_{18}
w	2.38 mm	± 100 μm	5.3	0.9	-3.8	0.5
t	0.46 mm	± 20 μm	1.2	-0.7	-0.5	0.5
r	46.36 mm	± 100 μm	-1.0	-0.1	1.6	-0.5
α	25.3 deg	± 80 μm (± 0.1 deg)	-0.1	-1.4	0.4	1.1
β	90.0 deg	± 10 μm (± 0.5 deg)	-0.8	0.3	0.5	-0.3

- Harmonics are most sensitive to shim width and thickness
- Tighter tolerance can be achieved and hence smaller impact on the harmonics

Impact of shim displacement (2D cases)

<u>Translation</u>



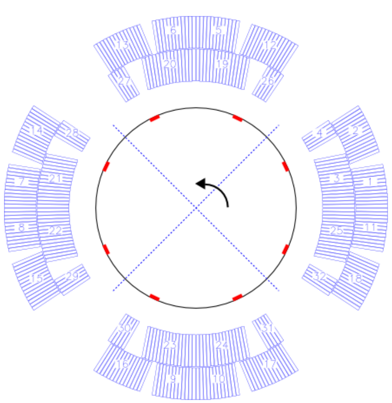
- Sensitivity [unit/mm] for translation within ± 0.2 mm

	Δb_3	Δb_5	Δb_7	Δb_9	Δb_{11}	Δb_{13}
$+\Delta x$	0.2	-9.5	1.5	0.3	-0.7	16.9

	Δa_3	Δa_5	Δa_7	Δa_9	Δa_{11}	Δa_{13}
$+\Delta y$	-0.3	-9.5	-1.5	0.3	0.7	16.9

Feed-down from large b_6 and b_{14}

<u>Rotation</u>



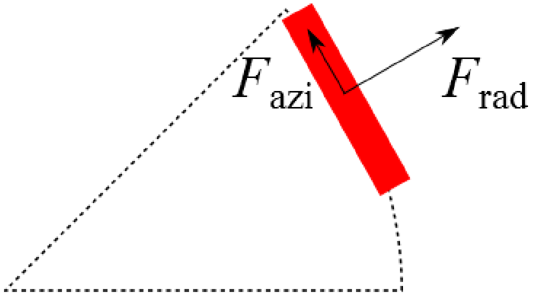
- Sensitivity [unit/degree] for rotation within ± 1 degree

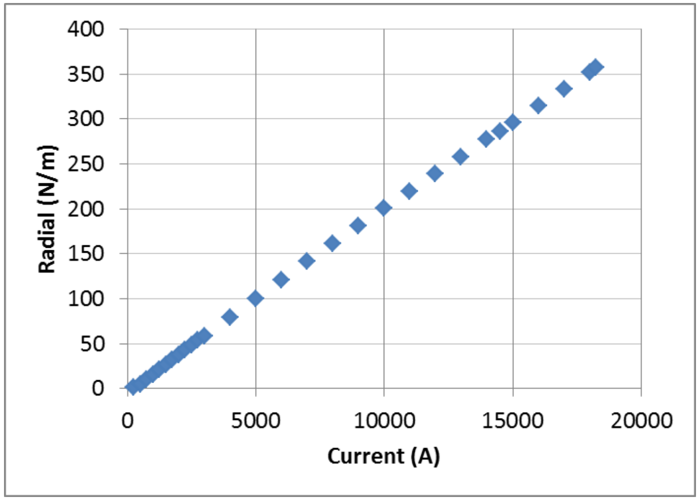
	Δa_6	Δa_{10}	Δa_{14}	Δa_{18}
$+\Delta\alpha$	-10.2	2.1	13.5	-5.4

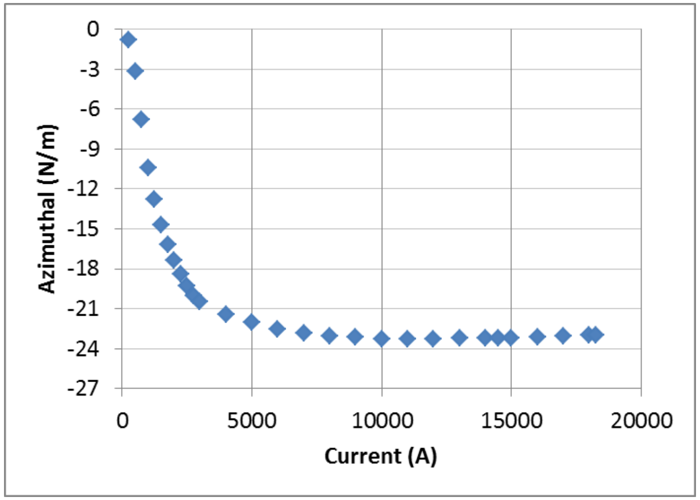
- Negligible impacts on allowed terms
- Same sensitivities apply with combined displacement modes

Force on the shims

- Analysis of the forces on magnetic shims to evaluate their mechanical stability
- Identical and symmetric shims assumed
  - Zero net force on the shims
  - One octant is considered



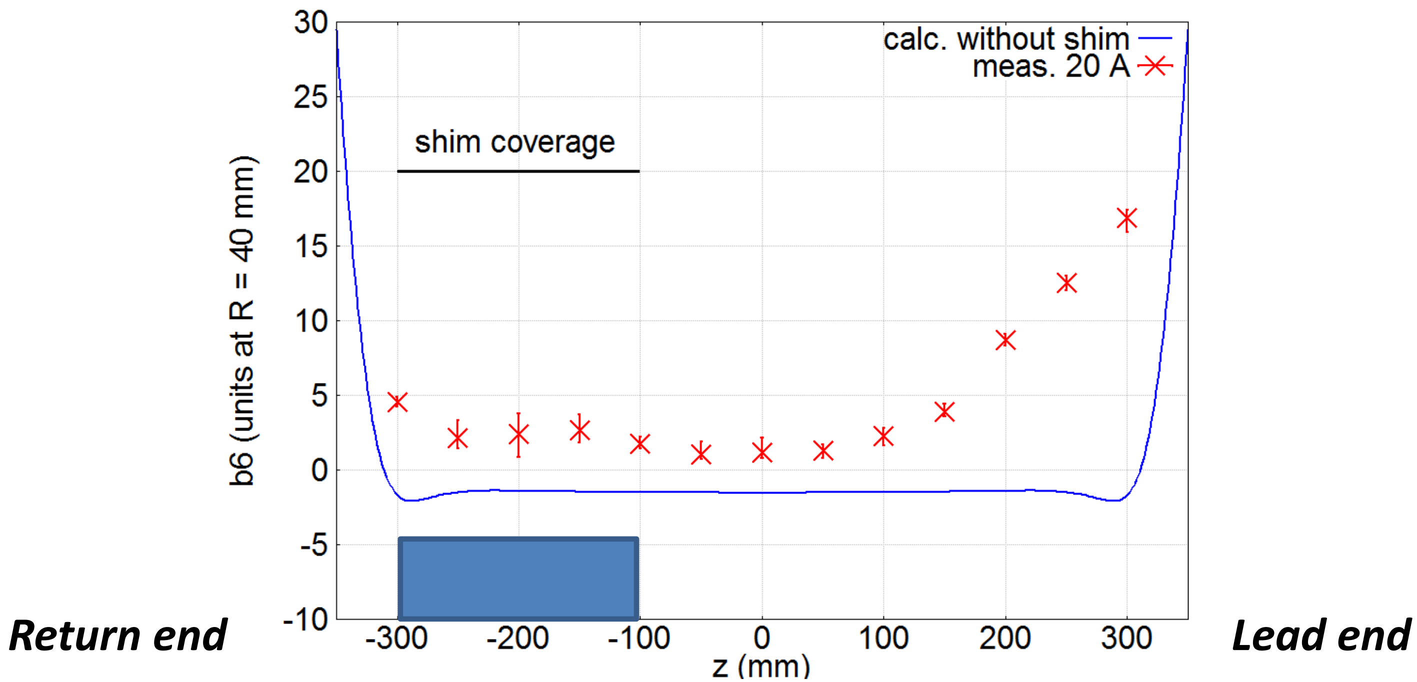




- Radial force scales with current, 350 N/m at short-sample limit (150 kPa). Dovetail groove and epoxy bonding is applied to counteract the radial force
- Negligible azimuthal force

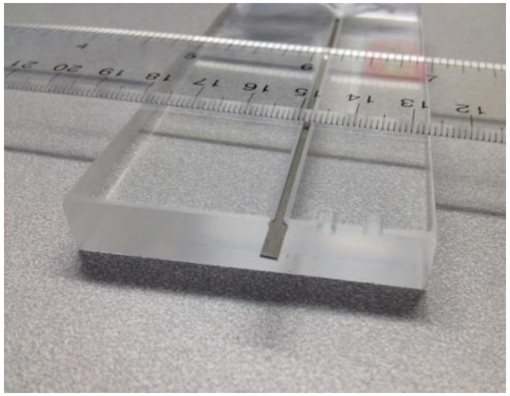
Longitudinal shim location

- Each shim is 200 mm long and cover partially the magnetic ‘straight’ section with minimum impacts from layer ramp and coil ends
  - Comparison of harmonics inside and outside the shim coverage
  - Probe length is 100 mm. An integrated effect is available when the probe is partially covered by the shim

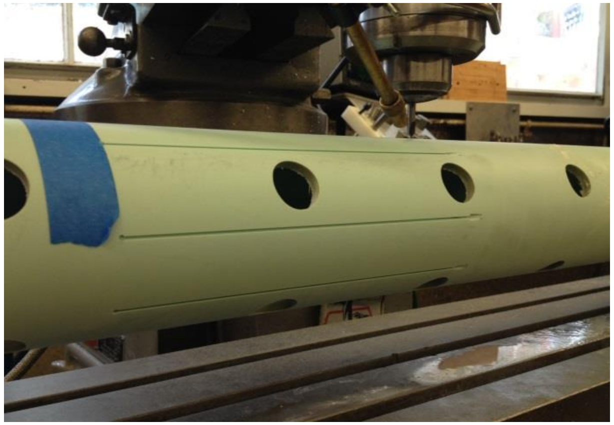


Persistent-current shims fabrication

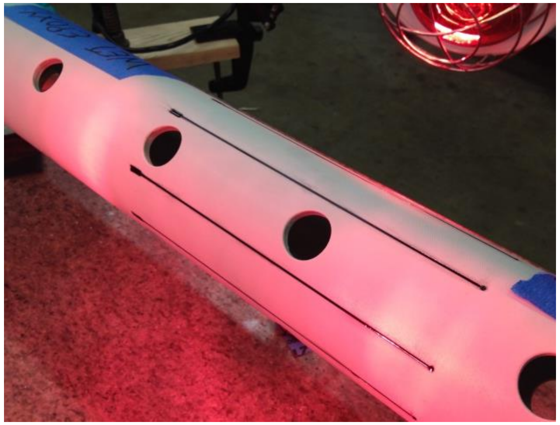
Dovetail groove and shim test fit



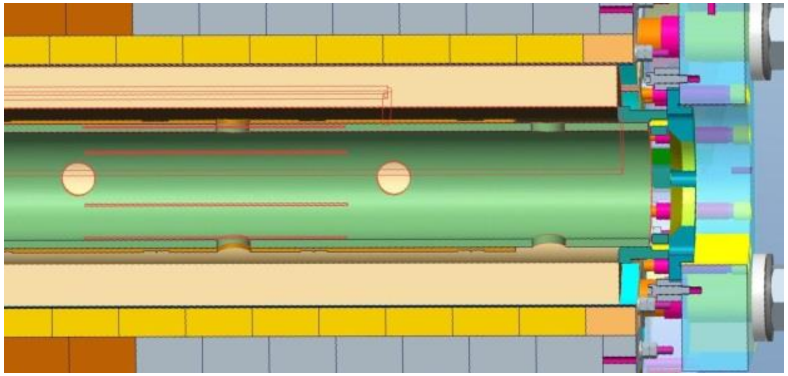
Machine the grooves on a G10 tube



Sealed with epoxy



Integration into the magnet aperture



Warm measurements of HQ02b

- HQ02b was used as a first test bed to study the shim fabrication, installation and compatibility with magnet cold operation

- Warm measurements are indispensable to define the geometric field errors and guide the correction scheme implementation

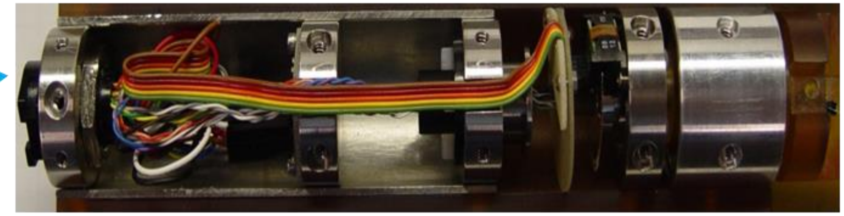
- Shims were installed after the adjustment of magnet pre-load
- Warm scan of HQ02b using a new FNAL measurement system to
  - Prepare for future warm measurements after magnet assembly
  - Verify the measurement system performance
  - Validate the shim analysis/computation

- Measurement protocol and data reduction
  - Warm scan along the bore, +/- 20 A to remove remnant field effects
  - 100 measurements at each step for better statistics
  - Scans before and after applying the shims
  - Measured data has centering and feed-down correction

FERmilab Rotating-coil Encapsulated Tesla-probe (FERRET) system

- XY accelerometers (gravity sensor)
- slip rings
- encoder
- bearing block
- Printed-Circuit Board (PCB) probe
- PCB support structure (3D-printed 'ABS Plus' plastic with carbon-fiber inserts)
- outer shell
- bearing

45mm ferret **(disassembled to show internal components)**



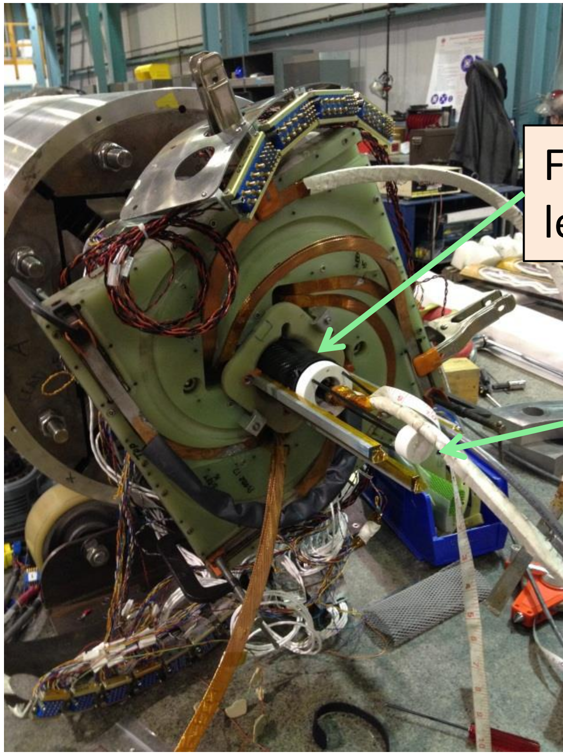
XY accelerometers   slip-rings   encoder   bearing block

64 mm OD Ferret (HQ02 meas.)

- **Radius of outermost PCB trace: 29.5mm**
- **Overall length 0.8m**
- **2 PCB probes: each 100mm long , with 16 turns * 10 layer sense coil. Analog bucking of dipole and quad with buck ratios > 1000.**
- **Total 7 channels: 3 probe signals (UB, DB, DQB), encoder index, encoder A-pulse (500 counts/rev), and X/Y accelerometers**
- **Rotation speed 3 Hz**

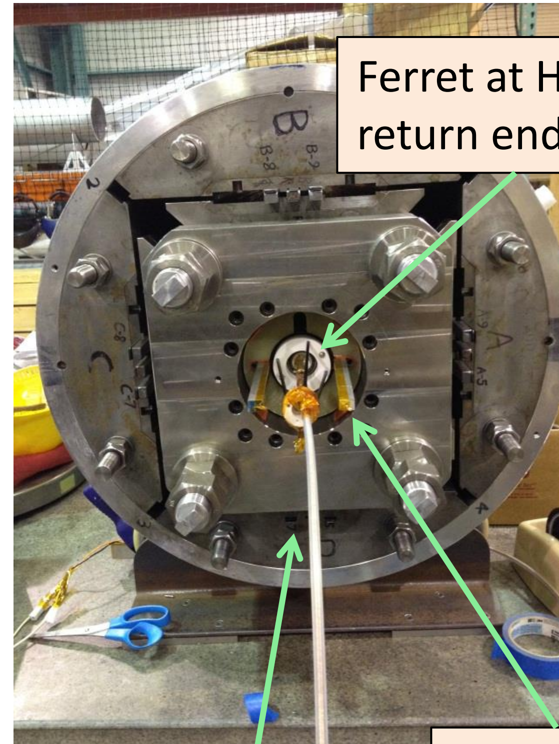
non-magnetic (phosphor-bronze) flex drive (to external DC motor):

HQ02b Warm Measurements Set-up



Ferret at HQ02b lead end

Signal cable and positioning tape



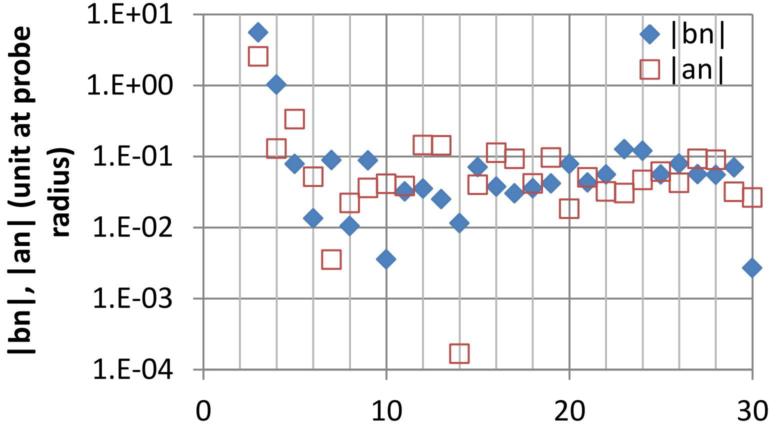
Ferret at HQ02b return end

Guide rails to support probe

Flexible drive shaft

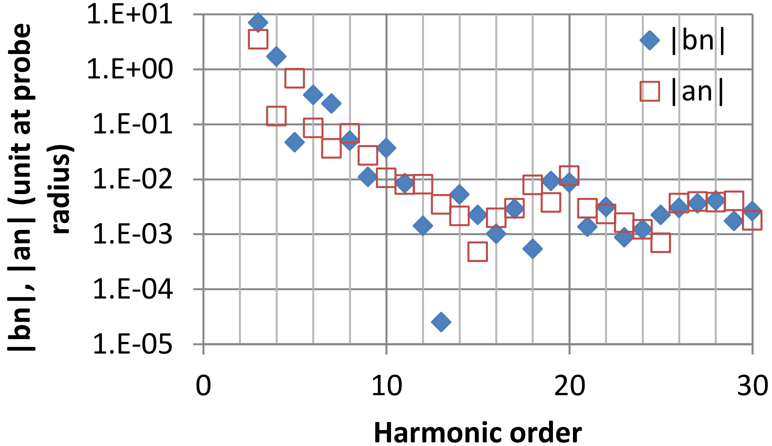
Additional tests were performed to understand magnet/probe coordinate system – here a steel rod is attached to the ferret outer tube to confirm signal polarity and start angle

Probe resolution



HQ02a measured at FNAL VMTF, 10A with 47mm dia. probe

~0.05 unit resolution

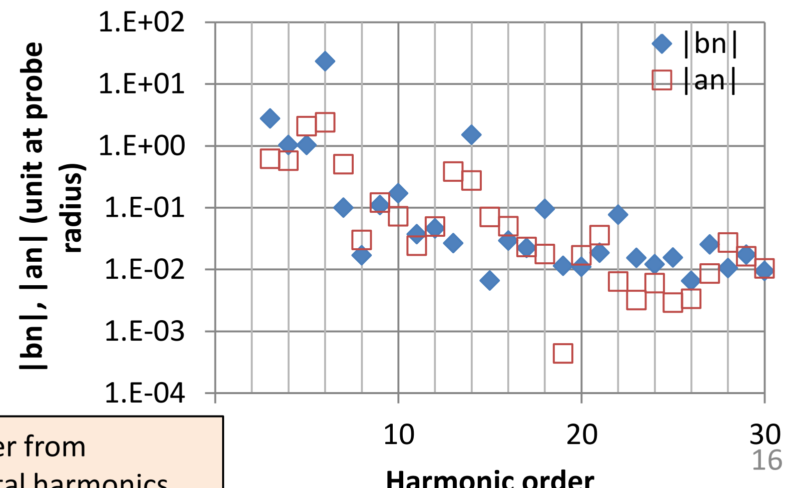


HQ02b measured at LBL, 20A with Ferret system (probe dia. 59mm)

~0.005 unit resolution

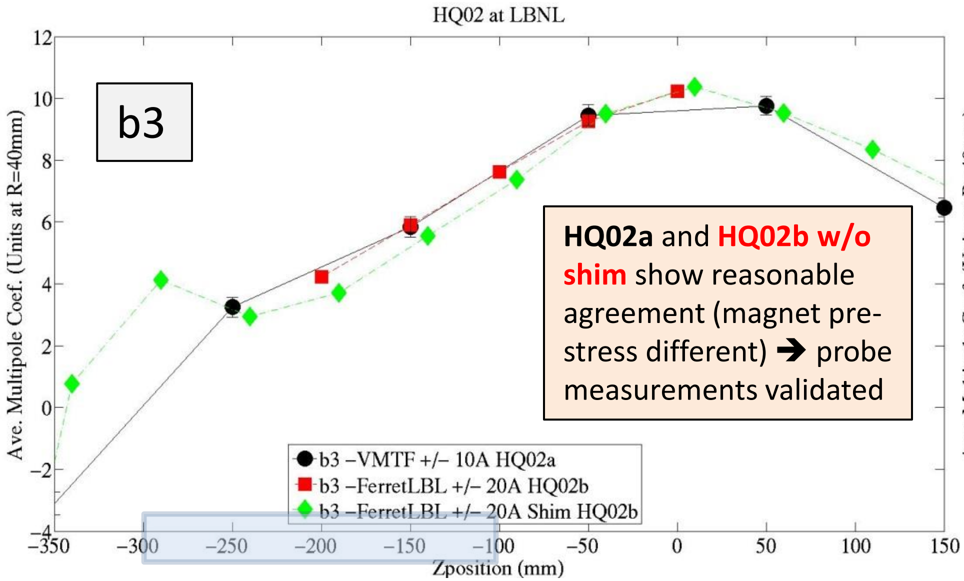
HQ02b resolution w/ Ferret in the vicinity of the shim

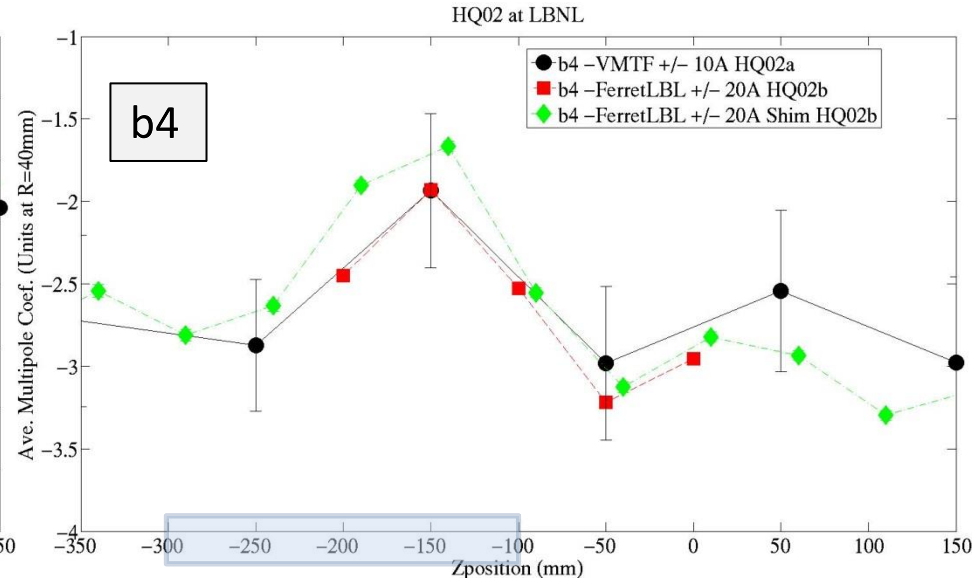
~0.05 unit resolution



In shim region, spurious harmonics may be larger from vibration effects owing to larger non-fundamental harmonics

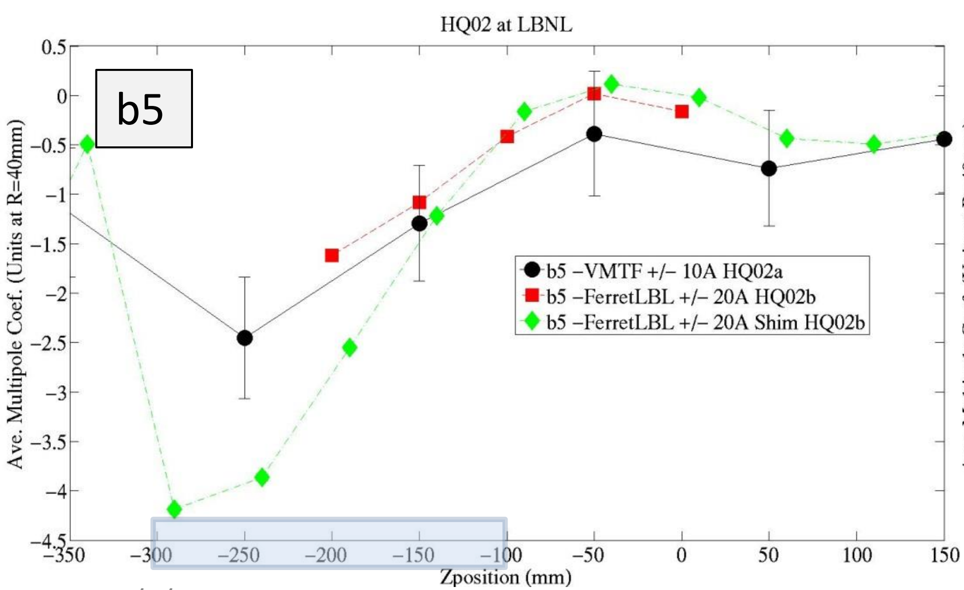
Measurement Results w/ and w/o shims – b_n

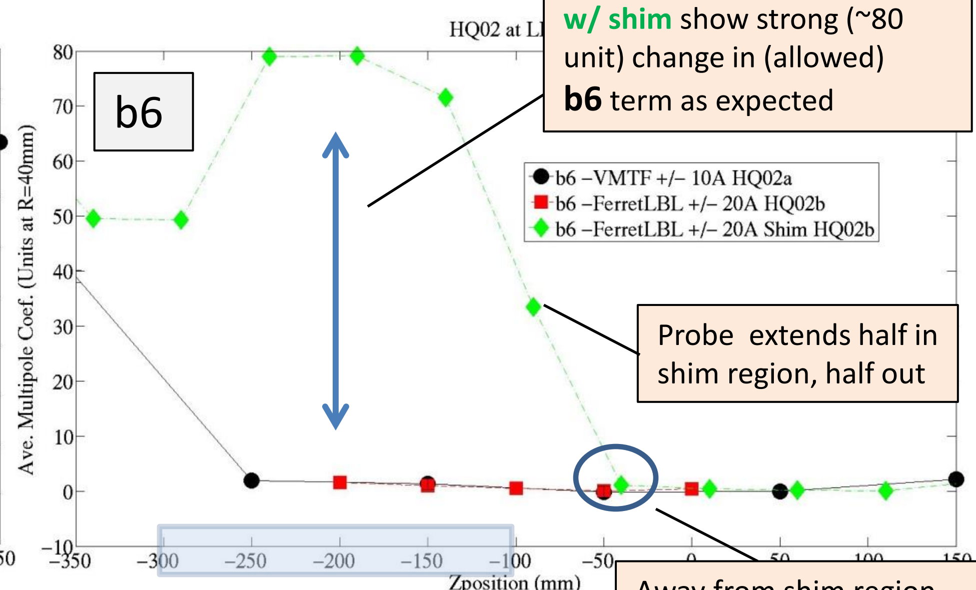




Appx. shim location

HQ02b w/o shim and HQ02b w/ shim show strong (~80 unit) change in (allowed) **b6** term as expected

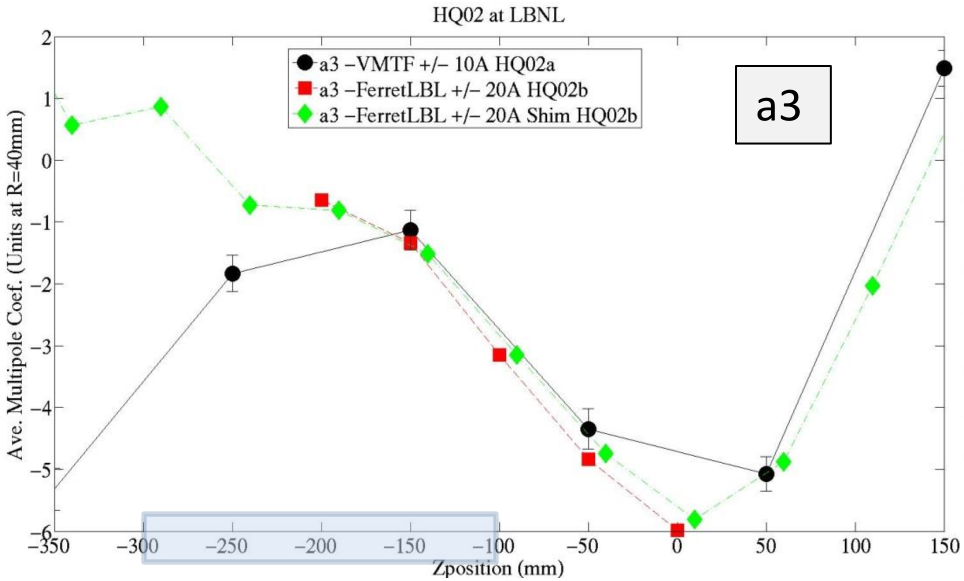


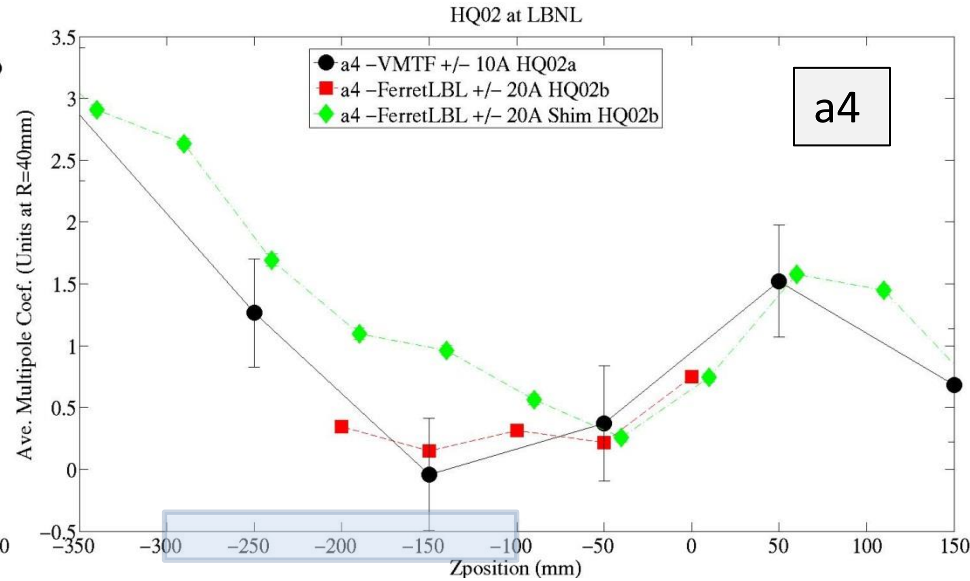


Probe extends half in shim region, half out

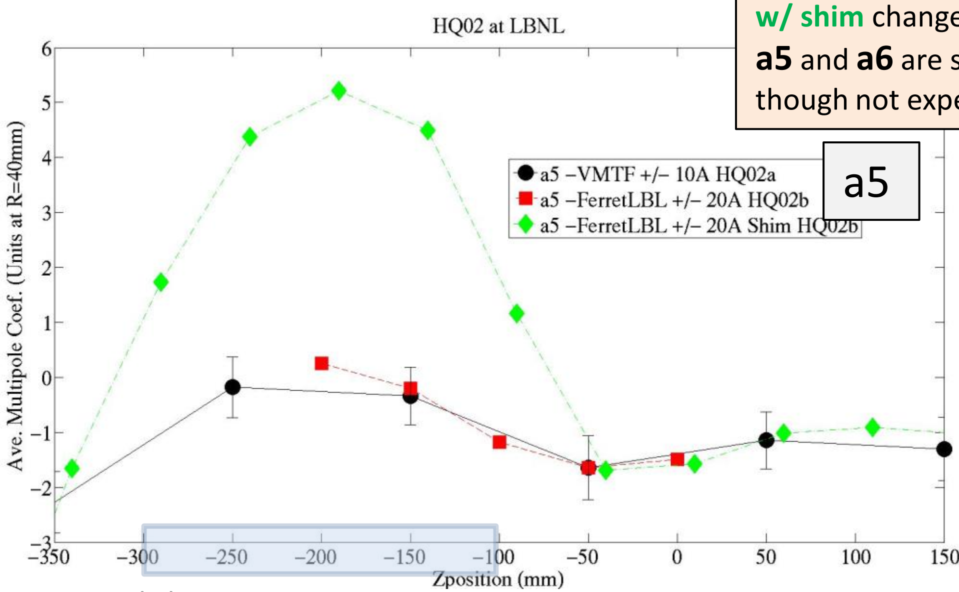
Away from shim region, there is little difference

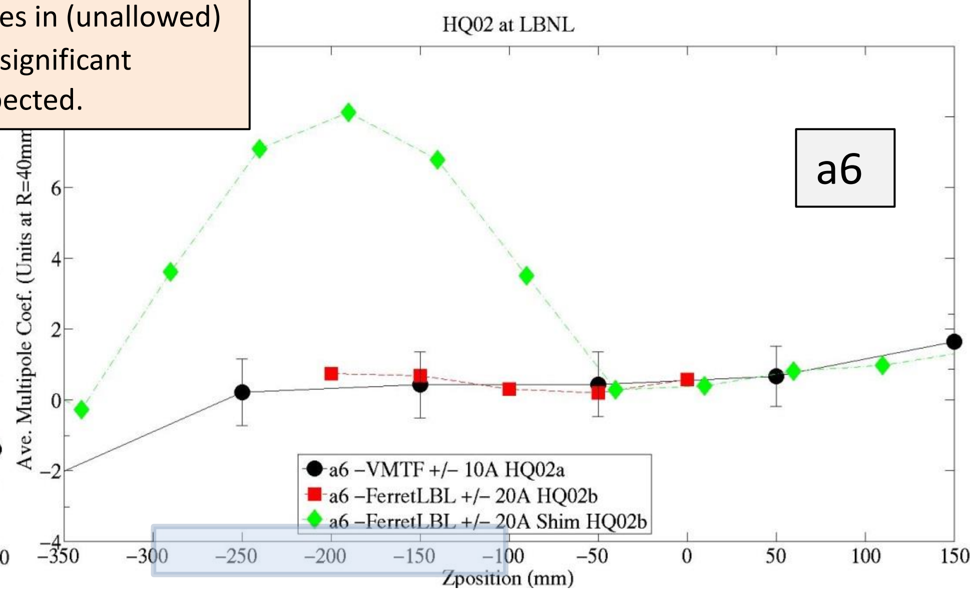
Measurement Results w/ and w/o shims – a_n



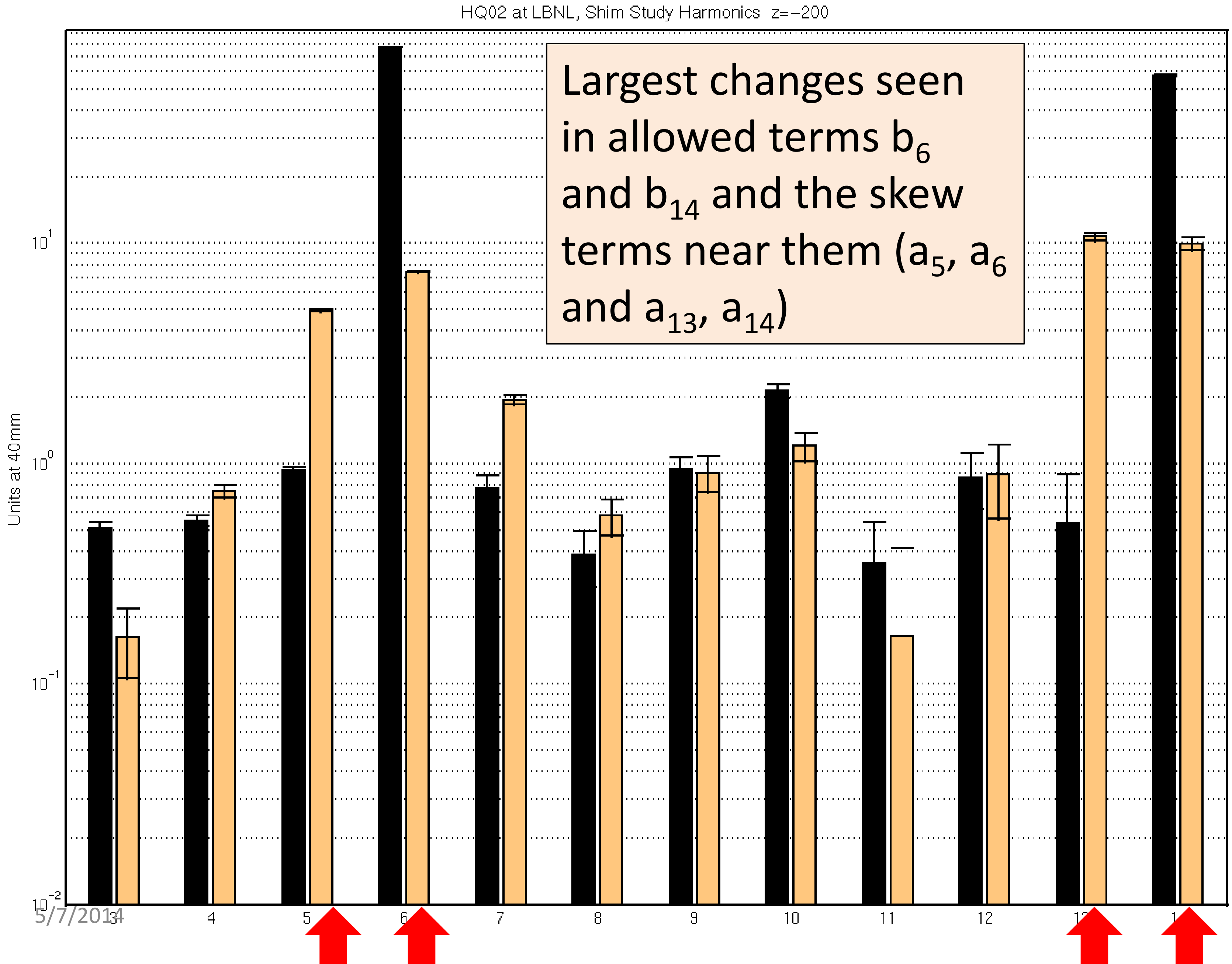


HQ02b w/o shim and **HQ02b w/ shim** changes in (unallowed) **a5** and **a6** are significant though not expected.





Summary of HQ02b Harmonics Change in Shim Region

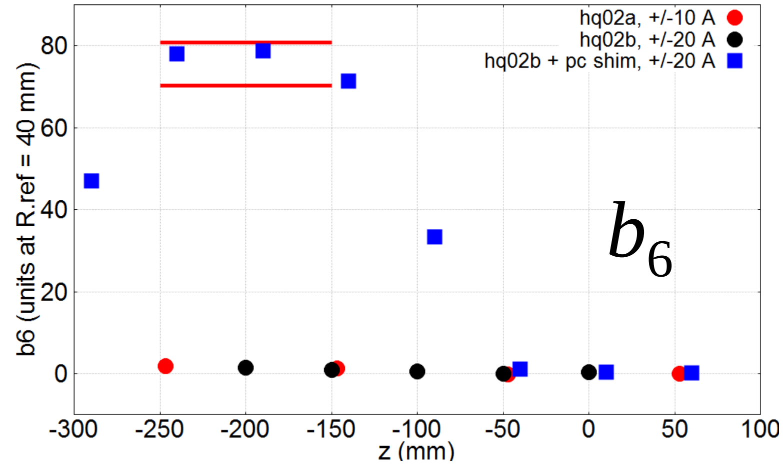


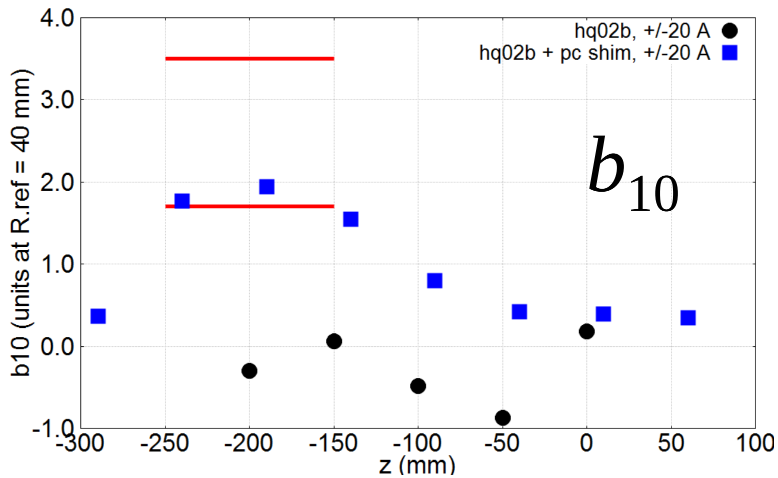
Largest changes seen in allowed terms b_6 and b_{14} and the skew terms near them (a_5, a_6 and a_{13}, a_{14})

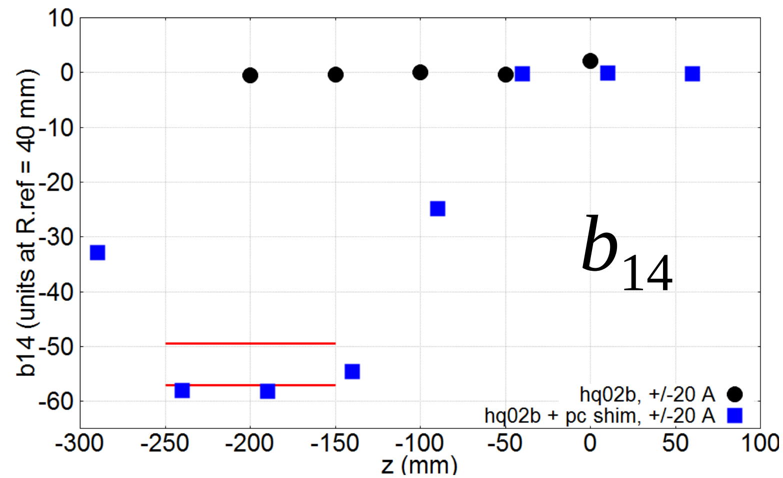
Allowed terms agree with computation

- Red bars are lower and upper bounds of the expected harmonics considering the uncertainty of the shim width (± 100 μm)

- Probe resolution sufficient to detect high-order terms

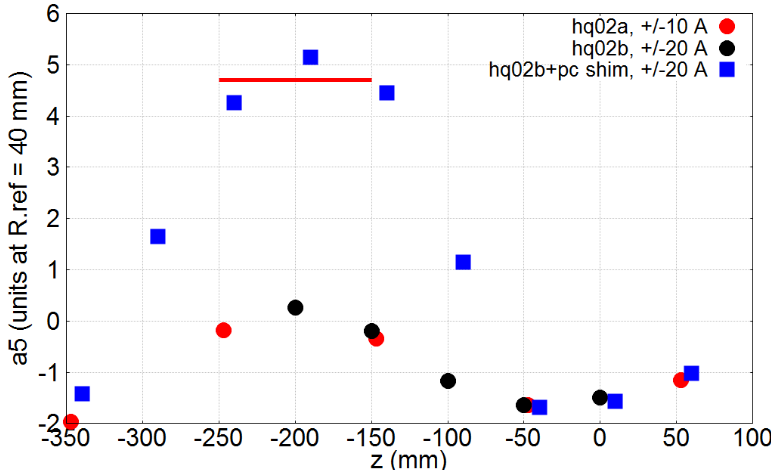


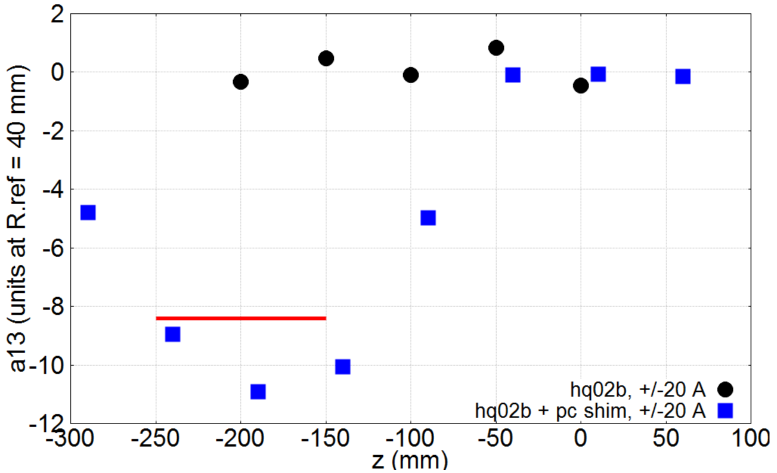




Observed a_5 and a_{13} attributed to off-centered tube

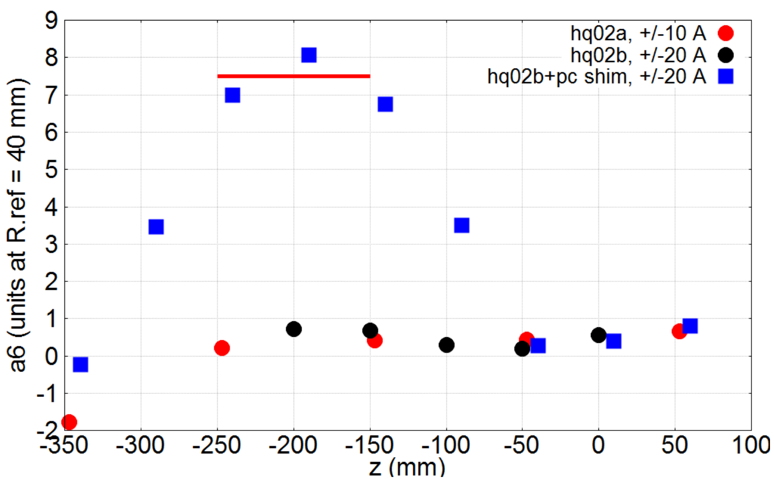
- Assuming shims on the tube are uniform and symmetric
- Δy = -500 μm can explain the measured a_5
- This gives -8.4 units of a_{13}, 20% lower than the measurements

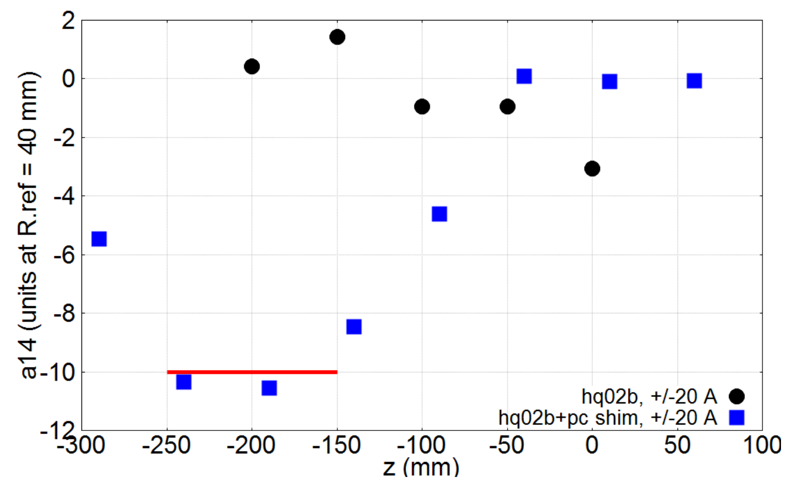




Tube rotation caused a_6 and a_{14}

- The measured a_6 suggests a rotation of -0.75 degree (clockwise, -600 μm)
- This leads to -10 units of a_{14}, consistent with measurements





- The measured harmonics suggests a the displacement of shim tube
  - Vertical displacement of the tube center for -500 μm
  - Clockwise rotation of the tube for -0.75 degree (-600 μm)
- In future installations, can use the warm measurements to minimize these offsets

HQ03 field quality study plan

- HQ03 will provide a reference for the field quality that can be achieved for QXF

- Monitor the harmonics during the coil assembly process with warm measurements to understand and perhaps control the origin of systematic variation of low-order harmonics

- Correction scheme implementation based on the experience from HQ02b
  - Implement geometric shims based on at warm measurements and verify during cold test
  - Persistent-current shims will be used and characterized with warm/cold measurements

Note: Ideally, we need two cold tests for field quality study to distinguish between the intrinsic field quality and the ability to correct the field errors

- One cold test before applying the correction scheme to identify the field quality baseline and establish the warm-cold correlation
- Test after applying the correction scheme to verify the performance

Summary

- Correction schemes for HQ geometric and persistent-current field errors are under development
  - One geometric shim and full set of persistent-current shims installed in HQ02b
  - No negative impact observed on HQ02b during the cold test
- FNAL Ferret warm measurement system with high-resolution probes was successfully used for correction scheme implementation and performance was verified
  - Measurements agree well with analysis of expected shim behavior
  - The Ferret system measurements will be used for warm measurements and to guide the geometric shim installation
- The HQ03 measurement plan can incorporate various field quality corrections. The goals and guidelines for these tests are open for discussion.